# Upper Limb Prosthetic Control Using Toe Gesture Sensors

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***Abstract*—A novel scheme to control upper-limb prosthesis with toe gesture sensing system is presented in this paper. In the proposed system, copper/polymer stack capacitive touch sensors fabricated on a flexible substrate, interfaced with electronics and wireless transmitters forms a smart sensing insole. The scheme takes advantage of the user making various gestures with their left and right hallux digits in the form of a Morse code. The touch results in change in capacitance of the sensors from 56±2 pF to 75±3 pF, which is readout by an interface circuitry. This is transmitted wirelessly to a computing system attached to the prosthetic hand, which controls it resulting in various upper-limb prosthetic gestures or grasp patterns depending on the corresponding mapped Morse code. The differential current at the output of the capacitor is converted into voltage through an integrator based capacitance-voltage converter(CVC), fabricated with 0.18-µm CMOS technology. The CVC is interfaced with off-the-shelf components. Details of the sensor, sensor interface and system's design, fabrication, validation, and overall functional assessment are presented in this work to show the potential of using toe gestures for upper-limb prosthetic control.**

## I. Introduction

Orienting technology, through new techniques, to rehabilitate the disabled and physically challenged and to help elderly is a noble cause, which will improve the quality of life of millions [1] [2] [3]. Prosthetics is one of the important research area where robotic technology serves its best for medical sciences. A novel scheme to control upper limb prosthesis is proposed in this paper to assist upper-limb amputees. Table I summarizes various prosthetic control techniques and their advantages and disadvantages. These control techniques ranges from simply implementable, cable-controlled, body-powered prosthetics to technologically challenging Targeted Muscle Reinnervation (TMR) based prosthetics control system. The effectiveness of a upper-limb prosthetic control method for wide-spread application depends on various factors such as cost-effectiveness, ability for easy fabrication, ruggedness, repeatability on daily use, easily installable, usability, ability to bring dexterity and accuracy to perform various gestures/associated activities etc. The current techniques have major drawbacks, namely: with EMG there is a need of relatively complex electronics/sensor electrodes and classification algorithms for implementing large gesture range [4]; EEG suffers from reliability issue and cost; sweating and placement positions of electrodes may interfere with reliable working in case of both EEG and EMG techniques; need of invasive

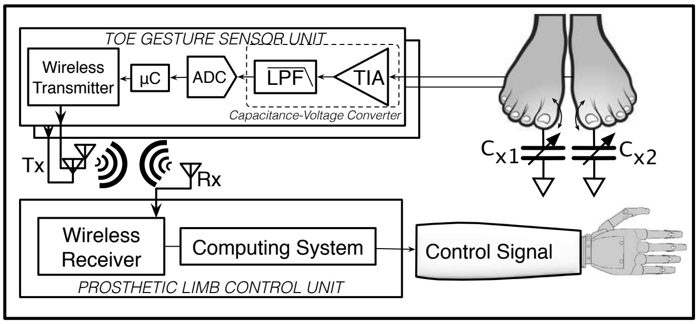


Fig. 1. Toe Gesture Upper Limb Prosthetic Control System Block Diagram.

surgery and associated high cost in case of TMR or implanted myo/neural interface etc.

In this paper we present a robust, non-invasive, simple, touch-based toe gesture sensor system for upper limb prosthetic control. A sensor interface system has been developed to demonstrate the effectiveness of this approach in this paper. The larger aim is to integrate this device in footwear, socks or insoles enabling them to control prosthetic limb and arm through gestures made in the feet.

The whole system architecture implementation, including sensors, circuits and system design is presented in Sections II. Section III presents the experimental results. Section IV draws the conclusion of the paper.

## II. Architecture Implementation

Prosthesis or an artificial limb replaces a missing body extremity. The present day technological interventions allow the functional prosthetic limbs to be controlled in a variety of ways such as TMR, EEG, ECG etc. In our proposed technique, by taking advantage of touch based gestures from functional toes especially the hallux digits, the prosthetic limb is controlled to perform a range of prosthetic multi-functional gestures or grasp patterns needed in various activities.

### A. System Design

The block diagram of the proposed system as an assistive prosthetic upper-limb control system is illustrated in Fig. 1. The toe gesture sensing system consists of flexible capacitive touch sensors integrated on a substrate with electronics forming a flexible smart insole. The user makes various gestures

TABLE I
COMPARISON OF VARIOUS UPPER-LIMB PROSTHETICS CONTROL TECHNIQUES

| Upper-limb Prosthetics Control Techniques | Advantages | Disadvantages | References |
|---|---|---|---|
| Body-powered upper-limb prosthesis controlled by cables connected to other healthy body parts | -Simple and easy to implement,<br>-No electrical power needed<br>-No external power requirements | - Limited number of gestures or grasp patterns are possible such as closing/opening of arms.<br>-Stress/exertion on other parts of the body | [5] |
| Switches based control of electrically-powered upper limb prosthesis | -With multiple switches several gestures or grasp patterns are possible | -Healthy other arm is required to control the prosthetic limb which restricts the dexterous two handed operation required for critical tasks | [5] |
| Electromyographic control of upper limb prosthesis | -Dexterous two handed operation is possible | -Need relatively complex electronics/sensors and classification, algorithms for implementing number of prosthetic gestures<br>-Electrode placement position is crucial and lack of optimal positions for shoulder level amputees or double-hand amputees<br>-Sweating may interfere with the electrodes' functioning<br>-Need of electric power | [4] |
| Brain Machine Interface using wireless transfer of classified/processed EEG signals for controlling upper limb prosthesis | -Intuitive thought controlled<br>-Non-invasive employing the EEG skull cap<br>-Dexterous two handed operation is possible | -Needs complex computation/signal processing for the EEG signals<br>-Accuracy may be be limited<br>-Sweating and placement positions of EEG electrodes may interfere with the sensors' working<br>-Requires use of conductive paste to improve signal quality<br>-Need of Electric Power | [6] |
| Targeted Muscle Reinnervation (TMR), Myo-neural Interface for controlling upper limb prosthesis | -Ability to bring functionality closer to a real arm with advanced coordination through brain control<br>- Dexterous two handed operation is possible | -Very complex<br>-Need of invasive surgery<br>-Not cost-effective currently<br>-Need of electric power<br>-Not medically approved yet | [1], [7] |
| Toe gesture control of upper limb prosthesis | -Simple and cost-effective<br>-A large number of prosthetic gestures or grasp patterns are possible<br>-Dexterous two handed operation is possible | -Possible false triggering due to other leg movements like walking, but could be solved by signal processing algorithms<br>-Need of electric power<br>-Necessity to get trained on various toe gesture codes mapped to different prosthetic gestures or grasp patterns | This Work |

or grasp patterns using their left and right hallux digits in the form of a Morse code where touch on left corresponds to "." (dot) and touch on right corresponds to "-" (dash). Currently capacitive sensors are used for sensing the toe gestures. However, the system could also be implemented using resistive and other flex sensors to detect hallux digits' gestures. In the present system, for the sensor interface, we have used a capacitance-voltage convertor (as shown in Fig. 4), designed and fabricated based on 0.18-µm CMOS technology [8] [9]. As the user generates Morse code signals with the toe movement, the codes are transmitted wirelessly. This is received by the control system that controls the limb to make various gestures depending upon the Morse code generated by the user. Using this approach a large number of upper-limb prosthetic gestures or grasp patterns needed to carry out day-to-day activities by the amputee can be performed in a cost-effective repetitive/rugged way in contrast to the other methods presented in Table 1. The i-limb$^{TM}$ prosthetic arm from Touch Bionics has been used in this work, which is currently controlled by a computer interface via Lab-VIEW. The change in the capacitance is thresholded to digital on-off signal which is transmitted wirelessly through bluetooth to the control system connected the prosthetics. Fig. 2 shows the implemented system in operation. PAN1555 low power Bluetooth 4.0 chips are employed for the present prototypes which communicated to LabVIEW. In future, the control system will be implemented in a single chip and embedded directly on the prosthetic limb. Table II summarizes the implemented Toe Gesture Sensing based upper limb prosthetic control system. The amputees have to get trained on getting the Morse code right through toe gestures in order to achieve the corresponding mapped prosthetic gestures or grasp patterns in upper limb prosthesis. This will enable them to carry out dexterous two-handed maneuvering as needed in their day-to-day activities. The approach presented here is versatile and could be adapted to control other daily used appliances by reserving gesture codes for controlling them and also it could be used by non-amputees.

### B. Sensor Design

A simple copper and polyethylene(PE) based flexible capacitance sensor has been fabricated and used as a touch sensor for the current purpose. The capacitive sensor (Fig. 3) consists of a smooth poly ethylene sheet of 200 µm thickness sandwiched between a crossed(20mm cross side with 7.5mm width) and square(25mm × 25mm) Cu sheet structures. The crossed Cu side faces the toe in the insole. The sensor assembly is flexible and is placed in the area under the hallux digit of the insole. Capacitance depends on the electrode area $A$, dielectric constant $\varepsilon$ and dielectric thickness $d$ is given by $C = \varepsilon A/d$. When the toe touches the sensor it will result in a added projected capacitance to the existing capacitance which is sensed by the sensing hardware.

In the current study, the crossed structure based capacitive touch sensing is found to be effective for the toe gesture based sensing. and a gentle touch or a feather touch is sufficient

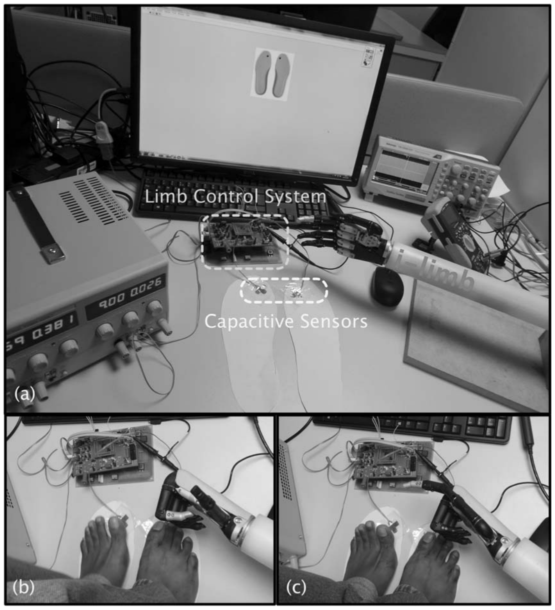


Fig. 2. Implemented Toe Gesture Sensing based Upper-limb Prosthetic Control System.

TABLE II
Toe Gesture Based Upper-limb Prosthetic Control System Summary

| Specification | Value |
|---|---|
| Supply Voltage [V] | 5 |
| Power Consumption [mW] | 210 |
| **Flexible Sensors** | |
| Materials | PE Sandwiched between Cu |
| Thickness [ μm] | 200 |
| Capacitive Sensor [pF] | 50 ~ 120 |
| **Integrated On-Chip** | |
| Technology [ μm] | CMOS 0.18 |
| Amplifier Gain [dB] | 98 |
| Amplifier PM [Degree] | 60 |
| Frequency [kHz] | 50 |
| **Off-Chip** | |
| ADC | ADC12D1800 |
| Microcontroller | Microchip PIC16F62X |
| Wireless Transceiver | PAN1555 2.4 [GHz] |

to make the sensor active. Alternatively, polymer film based off-the-shelf commercial (Interlink Electronics FSR400 series) force sensitive resistor has also been considered for the touch sensing. This sensor utilizes a thick polymer film as an active sensing material. Qualitative and quantitative summary of comparison between the capactitive and resistive sensors are given in Table III to choose the best sensor for the current work where the range of touch versus typical range of capacitance or resistance for these sensors are given measured with Agilent 6.5 digit 34461A and U1252B multimeters respectively. Upon application of pressure, the resistance decreases as given in

TABLE III
Comparison of the Capacitance and Resistance Values with of Representative Touch Sensors

| Touch Type | Pressure [kPa] | Resistance | Capacitance [pF] |
|---|---|---|---|
| No touch | 0 | >100 MΩ | 56 ± 2 |
| Feather touch | 3 - 5 | >100 MΩ | 75 ± 3 |
| Very gentle | 5 - 30 | 300kΩ -100 MΩ | 75 ± 3 |
| Gentle press | 30 - 90 | 75 kΩ-300 kΩ | 75 ± 3 |
| Button press | ~800 | 3 kΩ | 80 ± 3 |
| Full sensor touch | - | - | 107 ± 5 |

Table III from feather touch to gentle touch to button press touch(i.e. pressure needed to turn on a typical push button). Using resistive sensor, the resistance at feather touch and the no touch were found to be difficult to measure as it resulted in a resistance of >100 MΩ, beyond the upper limit of the multimeter whereas, in case of capacitive sensor a feather touch caused the capacitance to change from 56±2 pF to 75±3 pF. This aspect adds value to the capacitive sensor as it is very sensitive to the feather touch and hence no exertion is needed while making the toe based touch gestures. Further, capacitive touch sensor exhibited very less change when the touch is varied from feather to gentle press and button press touch as the projected area essentially remains almost same. However when the sensor is completely covered by touch with heel or palm it resulted in an increase in capacitance to 107 ± 5 due to increased projected capacitance area. Other aspects such as cost effectiveness, mechanical stability and simple fabrication method makes it more advantageous. However, capacitive touch sensor requires a conductive object/toe digits to be at very close proximity to work. In this regard flex/resistive

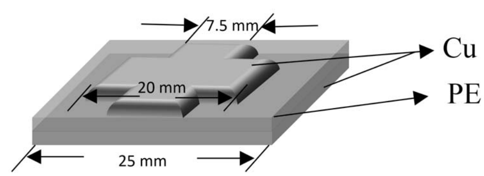


Fig. 3. Schematic of the Flexible Capacitive Touch Sensor Stack

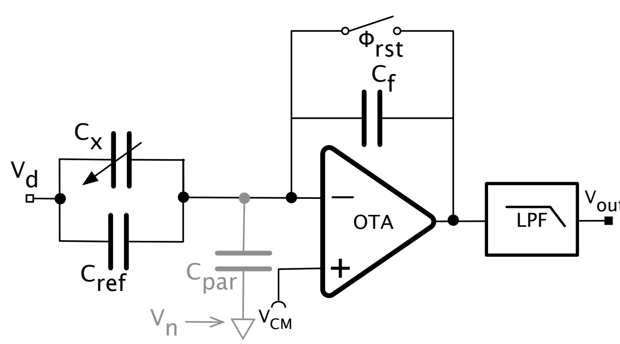


Fig. 4. Schematic Drawing of Capacitive Sensor and Integrated CVC.

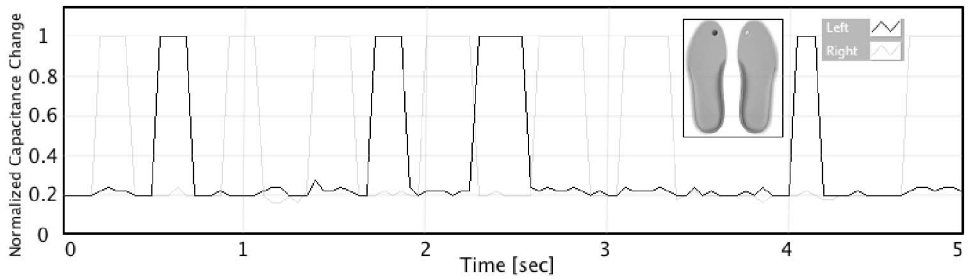


Fig. 5. Waveform showing the normalized capacitance change for random toe gestures logged in LabVIEW GUI.

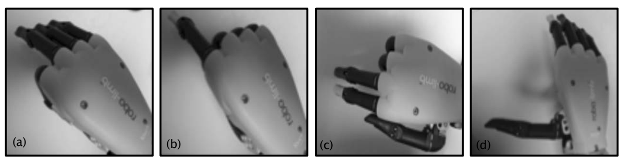


Fig. 6. Various iLimb$^{TM}$ Gestures achieved through mapped Toe Gestures.

sensors are better.

### C. Circuit design

The basic circuit of the capacitance to voltage converter (CVC) is shown in Fig. 4. In this scheme, reference capacitance ($C_{ref}$) is the mutual capacitance between a sense channel and a drive channel, $C_x$ is the capacitance change signal induced by a touch operation, $C_p$ is the parasitic capacitance of the sensor channel to the ground, $C_f$ is the feedback capacitance of the charge integrator, $V_d$ is the drive voltage, and $V_n$ is the external noise voltage. The output voltage level is given by [10]:

$$V_{out} \propto \frac{(C_{ref} + C_x)V_d + C_{par}V_n}{C_f} \tag{1}$$

In this CVC there are two sampling and charge-transfer phases. During the sampling phase, the switch $\Phi_{rst}$ is closed and the voltage of $(V_d - V_{CM})$ is sampled on $C_x$. Afterwards, the drive voltage pump a charge of $(C_{ref}+C_x)V_d$ into $C_f$ when switch $\Phi_{rst}$ is opened. It results in a value of the output voltage $V_{out} \propto V_{CM} - C_x V_d / C_f$, when $V_d$ rise from 0 V to $V_{DD}$. The output voltage is changed to $V_{out} \propto V_{CM} + C_x V_d / C_f$ if the $V_d$ fall from $V_{DD}$ to 0 V. A low-pass filter suppresses the ripple caused by capacitance sensor offset.

## III. Results and Discussion

The normalized change in capacitance, received from the left and right toe gesture sensing system and recorded in labVIEW interface is shown in the waveform in Fig. 5. These values are thresholded and digitized to on-off binary data. The data from the left and right foot is analysed and the corresponding Morse code is used to perform a pre-mapped gesture. Fig. 6 shows the various gestures of the i-limb$^{TM}$. Currently, power to the toe-sensing unit is provided externally through a DC power supply unit, which in future will be implemented with inbuilt flexible battery/supercapacitor/energy harvesting unit within the smart insole.

## IV. Conclusion

A novel method of toe gesture based upper limb prosthetic control is presented in the current research. A simple Cu-PE foil based capacitive touch sensor has been fabricated and utilized for this purpose. Overall, the method proves to be practical, accurate, easy to implement, cost-effective at the same time enabling dexterous control of the prosthesis.

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